



Fundamental Aeronautics Program

Supersonics Project

Commercial Supersonic Variable Cycle Engine Modeling with
Application of Mixer-Ejector Nozzles

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GRC/Multidisciplinary Design Analysis & Optimization Branch/SIA

2012 Technical Conference
March 13-15, 2012
Cleveland, Ohio
www.nasa.gov



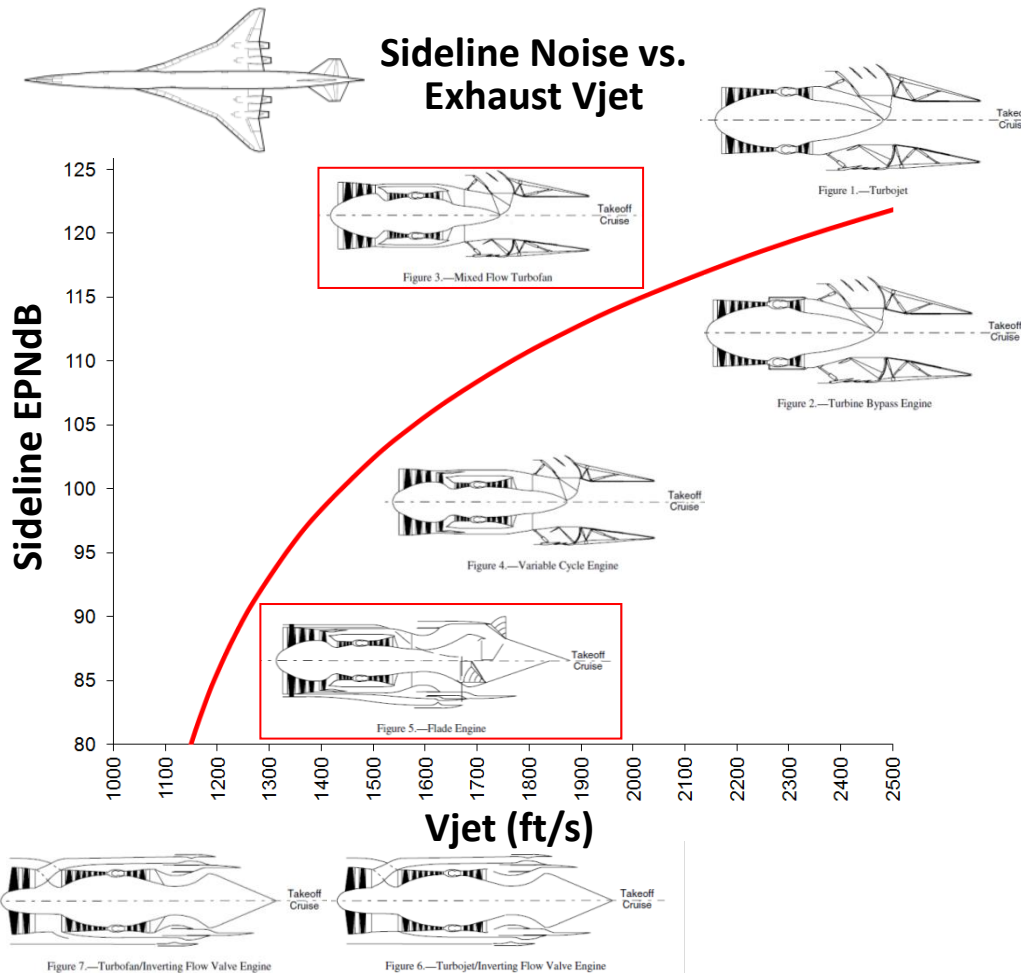


- Propulsion thermodynamic cycle modeling
 - Legacy from NASA's High Speed Research Program (HSR)
 - NASA's Fundamental Aeronautics Program Mixed-Flow TurboFan (MFTF) and Variable Cycle Engine (VCE) using NPSS
- Conceptual design and mechanical modeling
 - WATE++ (Weight Analysis of Turbine Engines)
 - VSP (Vehicle Sketch Pad)
- Key component modeling and integration
 - Turbomachinery modeling
 - Combustor and Emissions modeling
 - Suppressor Nozzle modeling
- Next-steps: exercising tools in integrated systems assessment

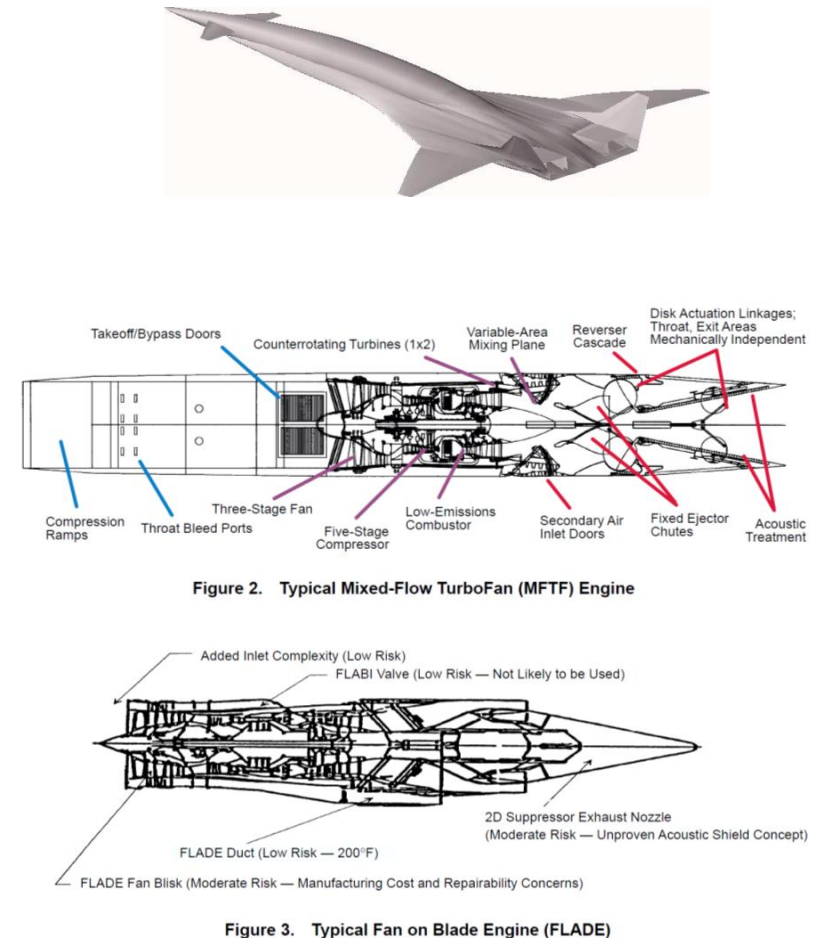
NASA HSR: Propulsion Cycle Explorations



• Early Program (<1995)



• End of Program (~FY2000)



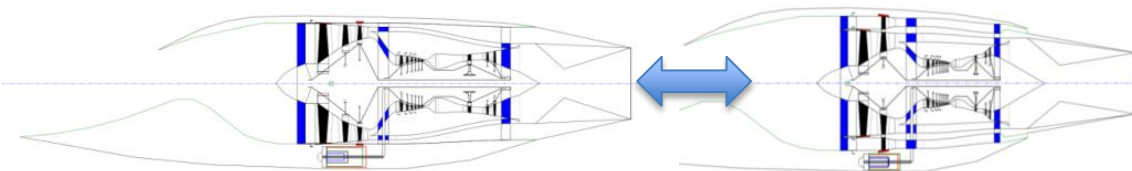
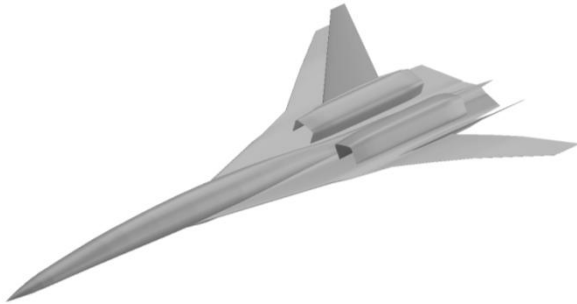
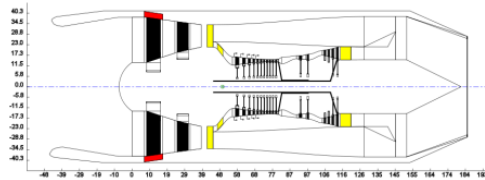
"A Comparative Propulsion System Analysis for the High-Speed Civil Transport"; NASA/TM—2005-213414; Jeffrey J. Berton, William J. Haller, Paul F. Senick, Scott M. Jones, and Jonathan A. Seidel; Glenn Research Center, Cleveland, Ohio

"Critical Propulsion Components Volume 1: Summary, Introduction, and Propulsion Systems Studies"; NASA/CR—2005-213584/VOL1; Pratt & Whitney West Palm Beach, Florida General Electric Aircraft Engines Cincinnati, Ohio

NASA FAP: APG Milestone using the N+2 Contractor MFTF Model and evolving NASA MFTF/VCE Modeling Improvements



- Focus on “Efficiency & Sonic Boom”
- Added focus on “Noise & Emissions”
- Increased design & operability parm.s Opt.



- Range = 4038 nmi (Range improved 3.7%)
- L/D=8.567 (L/D improved 1.2%)

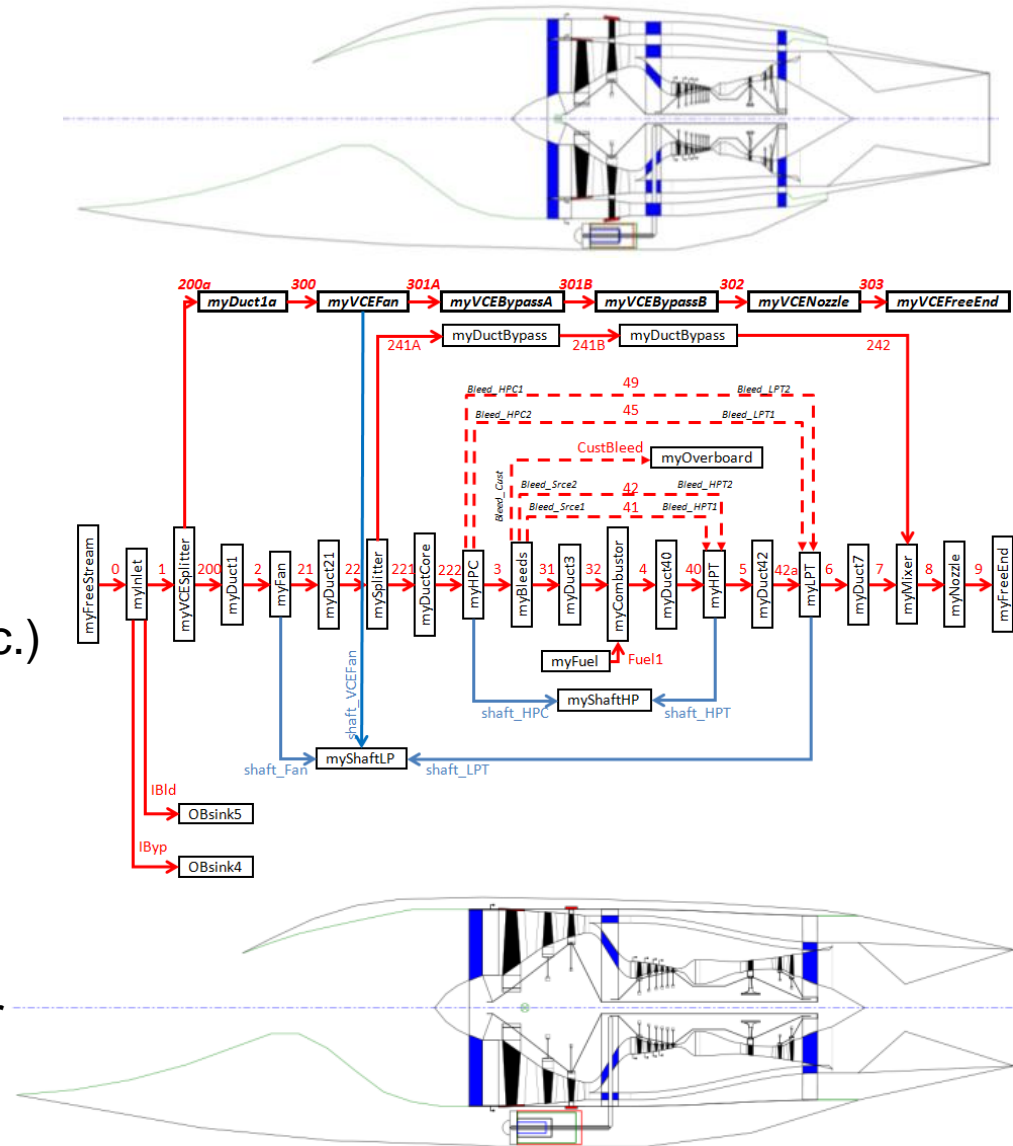
Cycle Parameters	Contractor N+2 MFTF Model	Optimized NASA MFTF from APG
FPR	2.2018	2.3312
OPR	39.219	36.921
EXTR	0.9	0.9481
TTR	1.1004	1.1235
V_j , fps	1554	1600
Net Thrust, lbs	41133	40810

Cycle Parameters	NASA MFTF & VCE Model tests	Optimized
FPR	1.6 – 4.4	TBD
OPR	25 - 50	TBD
EXTR	0.9 ~ 1.2	TBD
TTR	1.0 - 1.3	TBD
VCE bypass	0.0025 – 1.0	TBD
VCE tip FPR, alpha	1.2 – 2.4	TBD
Tech. Parameters		
T3 opMax (°R)	1600 - 1900	TBD
T4 opMax (°R)	3200 - 4000	TBD
HPT Tmblade (°R & cooling)	2300 - 3000	TBD
HPT Tmvane (°R & cooling)	2300 - 3000	TBD
LPT Tmblade (°R & cooling)	2300 - 3000	TBD
LPT Tmvane (°R & cooling)	2300 - 3000	TBD
A/C Integration Parameters		
Cust Bleed, HPX	1+,100 +/-	TBD
<i>Fan opAlpha/Sched.</i>	TBD	TBD
<i>VCE tipFan opAlpha/Sched.</i>	TBD	TBD
<i>Nozzle Des./op params/Sched.</i>	TBD	TBD
<i>Inlet Des./op params/Sched.</i>	TBD	TBD
V_j , fps	TBD	TBD
Net Thrust, lbs	41133	TBD

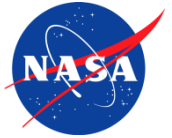
NASA MFTF and VCE Performance (NPSS) and Mechanical (WATE++) Models based on a Continuum Architecture



- MFTF/VCE architecture continuum allows for continuous design space optimization
- Turbine cooling & bulk metal temperature submodels, stress-based design
- Rule-based flowpath design (independent/dependent, guess functions, modified turbomachinery stage work-distribution methods, etc.)
- VCE cycle enables ~8% installed TSFC reduction via inlet-airflow management
- Added bypass & cycle variability enables acoustic Vjet contouring for T.O. while buffering the optimum supercruise engine cycle



Publicly Available Methods Improvements Critical to Supersonic Propulsion MDAO

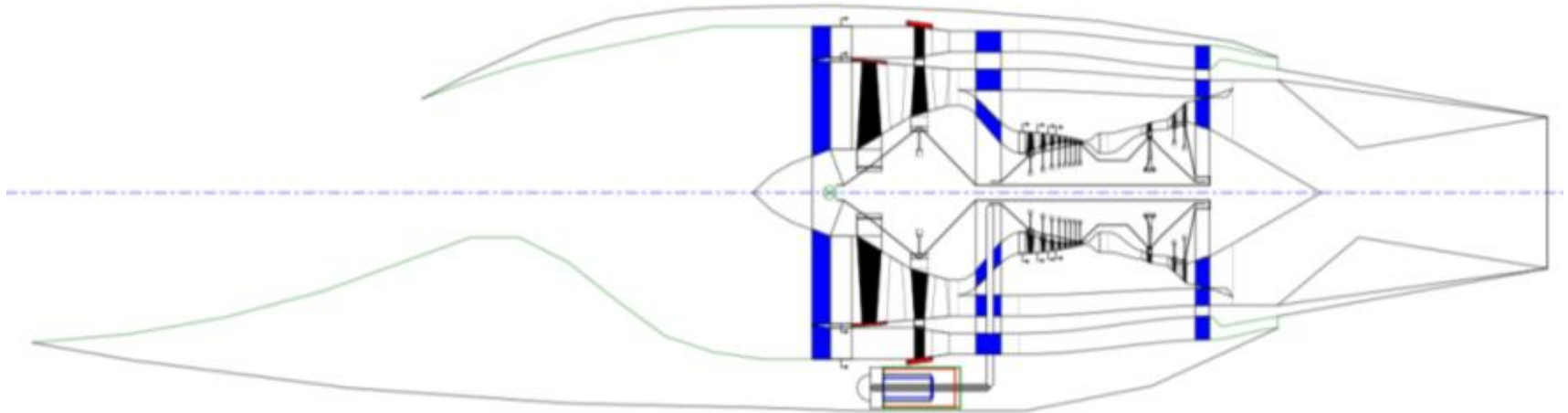


Performance vs. Acoustics/ Sonic-Boom

- Inlet design: NPSS approach, SUPIN
- Controls & Accessories packaging
- External Hi-Fi geometry parametric shaping (inlet/nacelle/nozzle)

Performance vs. Emissions

- Lo-Fi combustor design
- Lo/Int.-Fi combustor (reactor-network)
- Hi-Fi combustor design (parametric CAD & MDAO)



Performance vs. Weight/ Durability (Pervasive)

- Transformation matrix methods for stress-based design/analyses
- Internal Hi-Fi geometry generation (all components)
- Turbomachinery design & operability: NPSS-OTAC
- Materials & Structures database
- Parametric component reliability

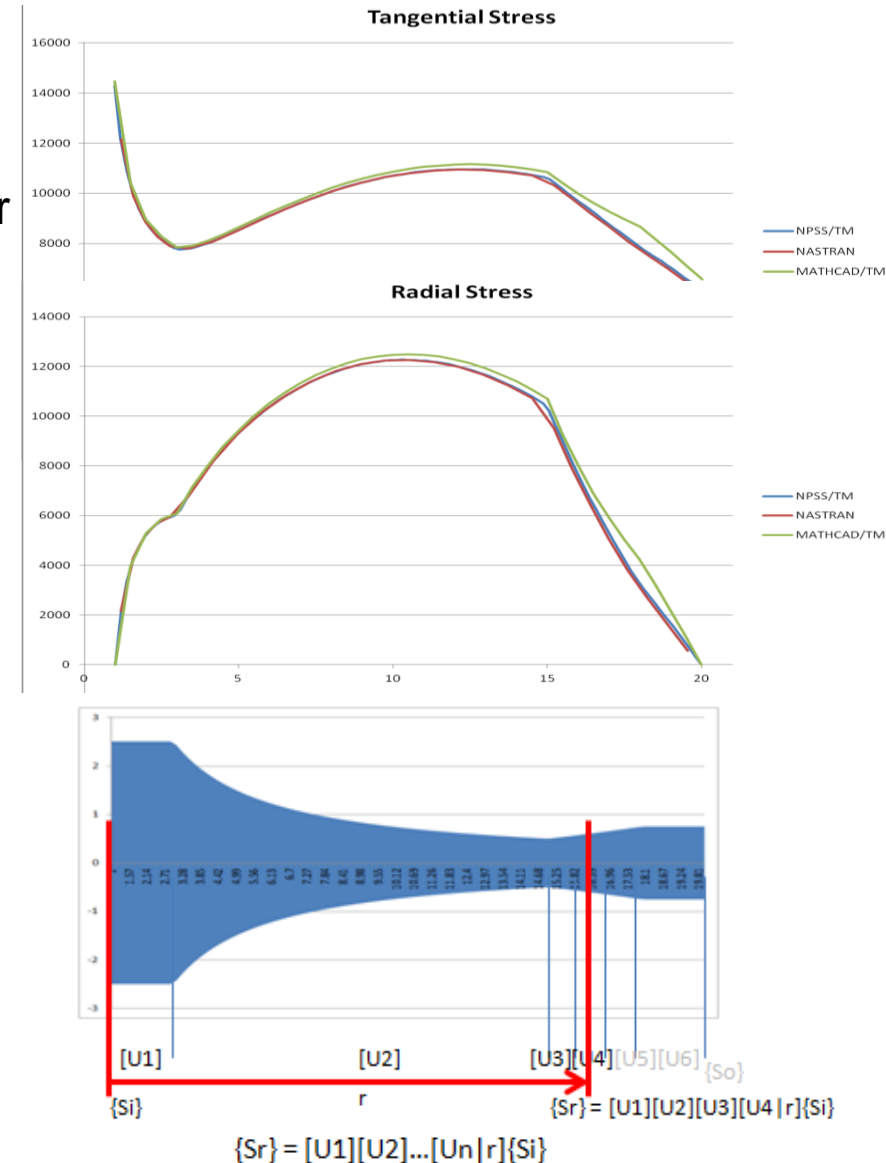
Performance vs. Acoustics

- DREA Nozzle performance
- HSRNoise acoustic maps
- ANOPP acoustics integration

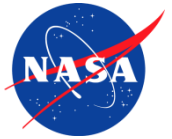
Structural Modeling extension of WATE++ using Transformation Matrix Methods



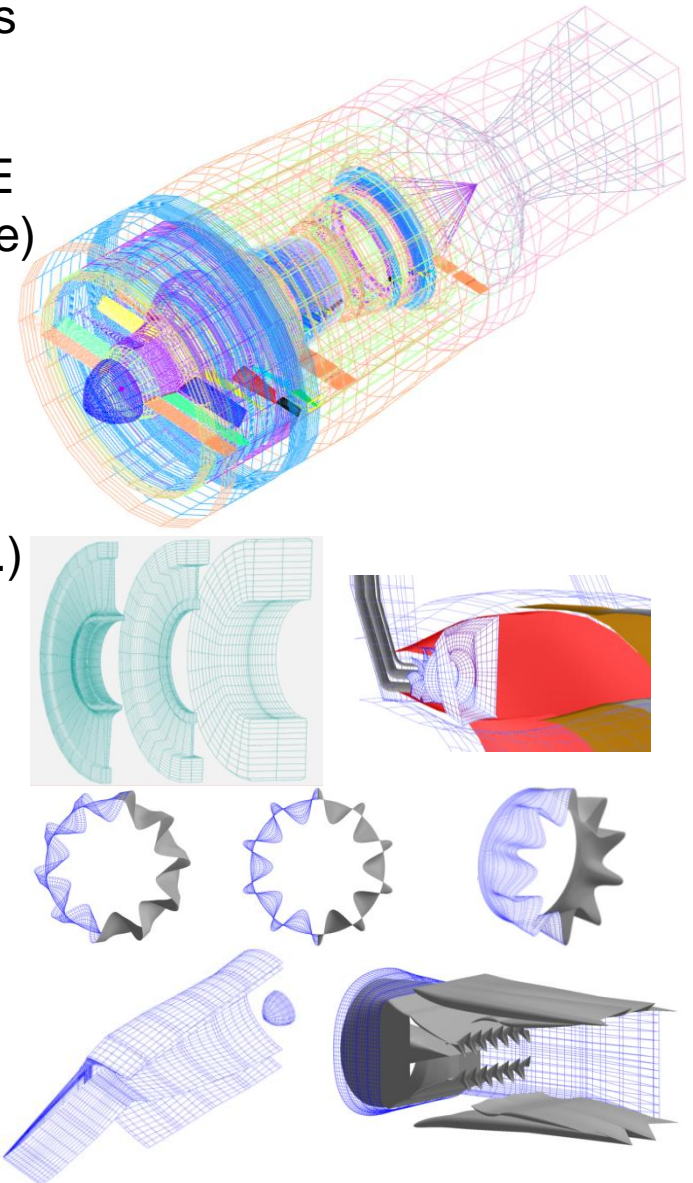
- Implemented extensible structural design/analysis utility for use within WATE++ (Lo-Fi) conceptual design tool
 - Completed Transfer-matrix method for disks (using NPSS matrix utilities)
 - Transfer-matrix method for blades
 - Transfer-matrix method for static beam/plates & shells (e.g. inlets & nozzles)
- Matrix formulation enables functionally graded materials definition and multi-directional stress computation
 - Captures material creep at sustained supersonic cruise
 - Enables more accurate geometry modeling of thermal soak & gradients
 - Preserves composite material directionality impacts



Geometry Modeling extension of WATE++ using VSP for use in Routine Hi-Fidelity Simulation



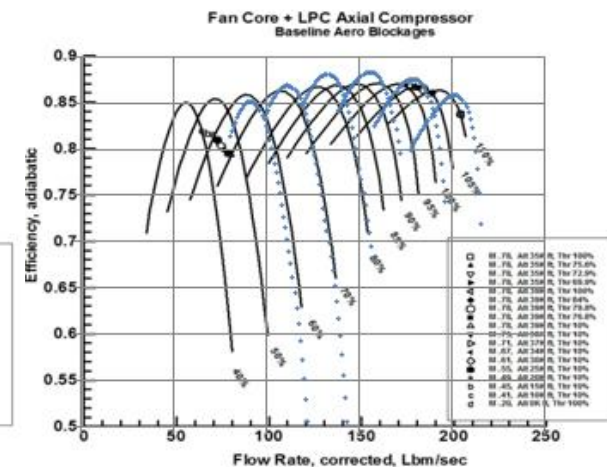
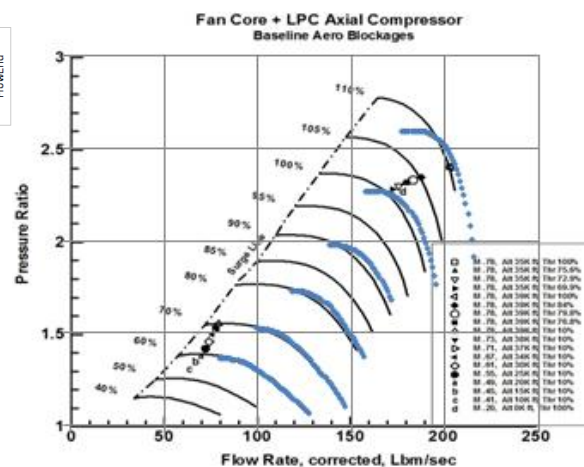
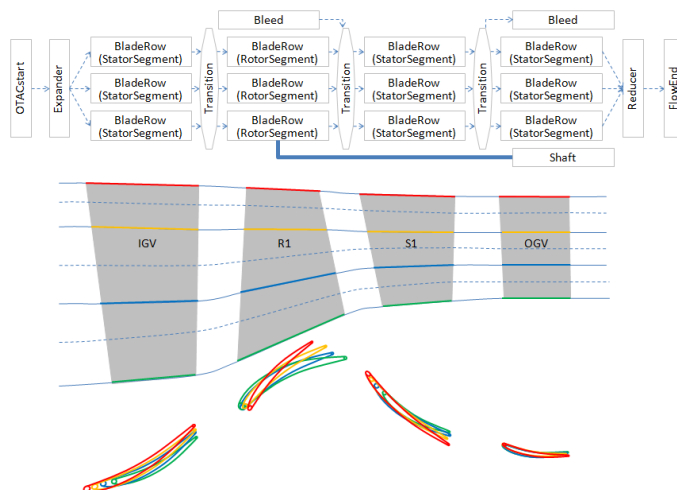
- Currently using interpreted NPSS/WATE++ viewers to produce VSP component .xml files
- Beta-version geometries in place for nearly all VCE engine components (some scripts to OpenCascade)
- Engaged in SFW NRAs to further improve VSP-Propulsion modeling (Cal-Poly, Georgia Tech)
- FUSE2 & Ms-wing classes allow exploration of 3D shaping (bypass ducts, mixers, inlets, nozzles, etc.)
- Evolving parameterization & geometry consistent with component design approaches:
 - Low-emissions Combustor elements
 - Nozzle & M/E suppressor elements
 - Inlet elements per SUPIN 1.2 (ref. Slater)
 - Suspended NPSS recoding of Slater methods due to excessive geometry of shock modeling for flow conditions
 - May revive subsonic diffuser element pending NPSS-OTAC radial flowstation development



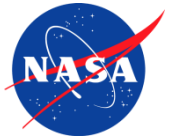
Turbomachinery Component Modeling using NPSS-based Object-oriented Turbomachinery Analysis Code (OTAC)



- Extended NPSS fluid ports allowing radial expansion/reduction of traditional 1D fluid port analyses to n-flowstations; built into new Consortium NPSS 2.4 release
- Leverages existing NPSS framework environment: solvers & utilities, shared objects (e.g. constituent loss models), thermodynamic continuity, etc.
- OTAC library of objects supports meanline and streamline turbomachinery analysis of axial-radial machines (engineering still in-progress)
 - Enables bladerow evaluation of novel turbomachinery concepts (counter-rotating bladerows, axi-radial meanlines, highly variable machines, etc.)
 - Several proof of concept models created (10 stage axial HPC, multi-stream fan, 2 stage axial HPT, 6 stage axial LPC)



Lo-Fi Combustor Design and Emissions Model using New Correlation-based Approach



- New non-proprietary correlation model using a similar *form* of the majority of existing EINO_x correlations but incorporating design parametrics:

$$\text{EINO}_x = a_0 * (\text{Pt}_3)^{a_1} * \text{EXP}((\text{Tt}_3 - 459.67)/a_2) * a_3 * \text{function}(\text{local FAR})$$

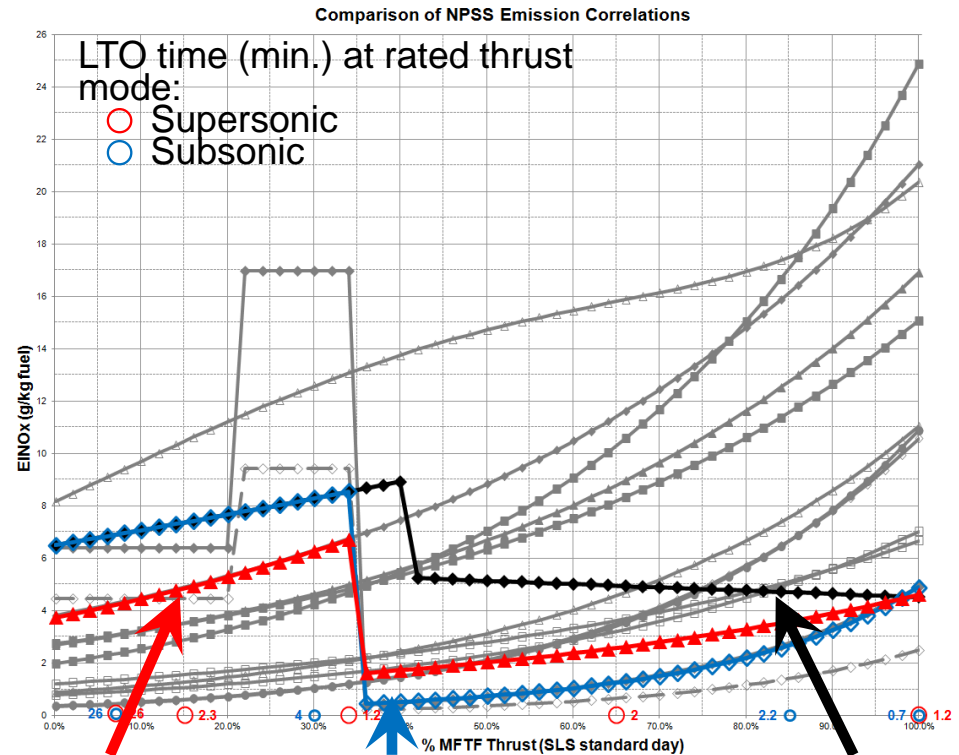
Calibration
Constant

Term influences Flame
stability reaction rate &
vaporization rate

Term influences thermal NO_x
formation & combustion delay thru
latent heat of vaporization

Term reflects mixing zone &
combustion zone NO_x
formation thru mixing geometry

- Term#1** & **Term#2** describe NO_x propensity; reminiscent form of the Clausius-Clapeyron equation for liquid (fuel) vaporization (inverse); allows alternative fuel types
- Term#3** combines FAR mixing & combustion reflects major injector & combustor parametric design features (atomization, swirlers, #injectors, etc.) & ignition time
- Sum of locally partitioned segments allows for pilot & fuel staging investigations, ΔP, %cooling, etc.



*New correlation appx.
of General HSR
configuration (no
calibrations applied)*

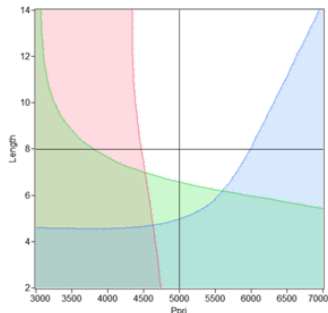
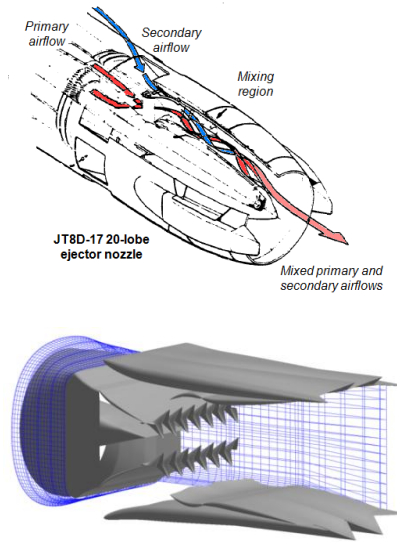
*Updated HSR & pilot
correlation per published
& unpublished Coord
memos*

*Early "General
HSR rules"
correlation with
pilot*

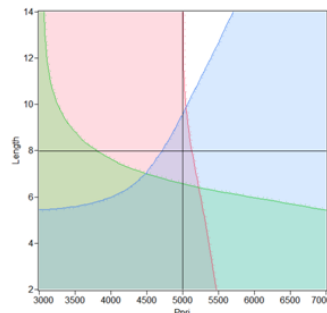
Suppressor Nozzle Design Performance & Acoustics Modeling using DREA/HSRNoise and ANOPP



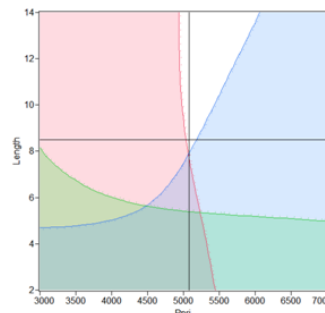
- Mixer-ejector nozzles have the potential to provide high thrust coefficients and reduced jet noise for supersonic aircraft, balancing nozzle vs. engine weight, size and complexity
- Low fidelity analysis tools for estimating performance (DREA) and acoustic (HSRNoise) characteristics have been integrated to perform multi-disciplinary design trades
- An initial design trade of “conventional” mixer-ejector nozzle geometry was performed using the VCE primary conditions, producing both performance and acoustic maps for subsequent vehicle MDAO using ANOPP



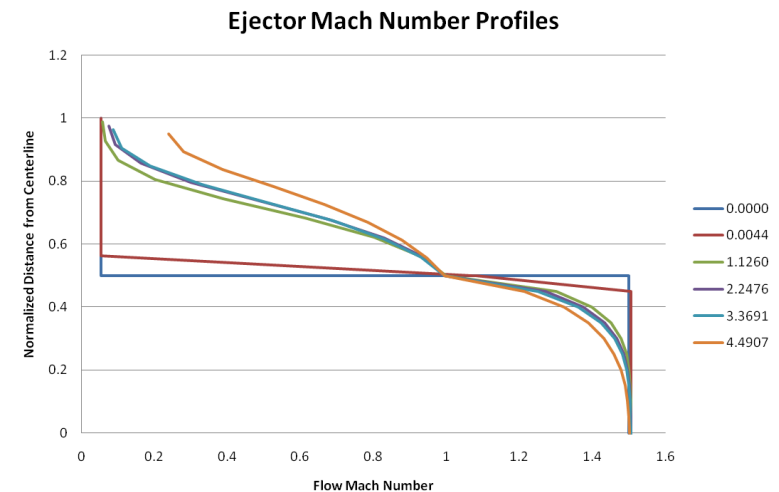
Gross Thrust > 20,000 lbf
CFG > 1.1
OASPL @ 120deg < 145 dB
Primary Pressure: 5000 psf
Length: 8 ft
Area Ratio: 1.75
Aspect Ratio: 3
Chute Angle: 10 deg



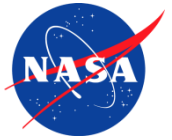
Gross Thrust > 25,000 lbf
CFG > 1.1
OASPL @ 120deg < 142 dB
Primary Pressure: 5000 psf
Length: 8 ft
Area Ratio: 1.75
Aspect Ratio: 3
Chute Angle: 10 deg



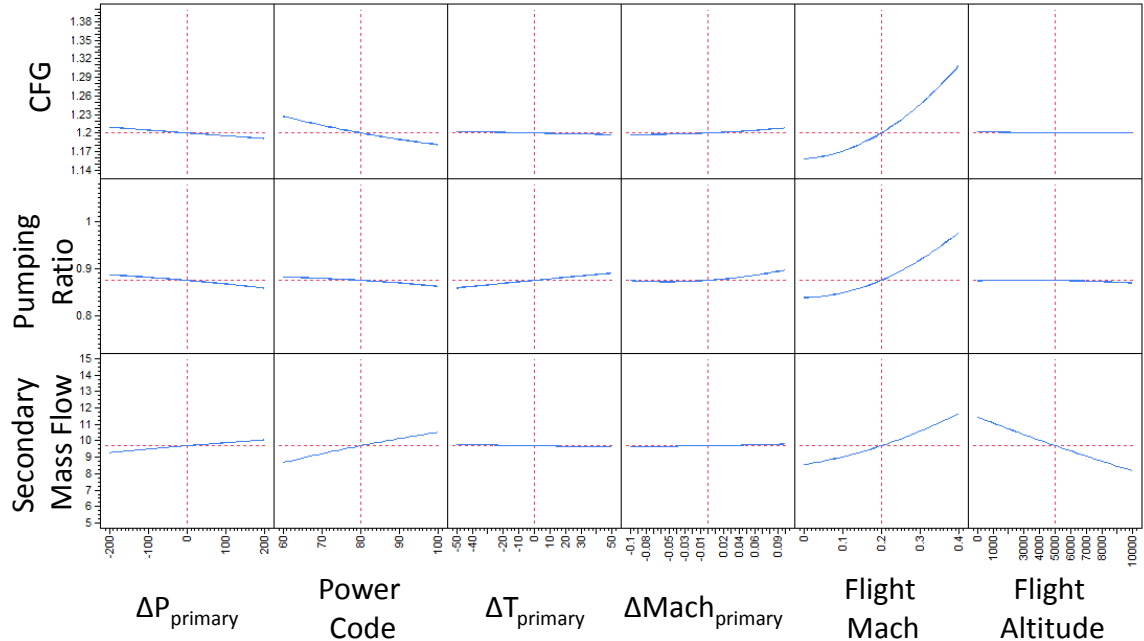
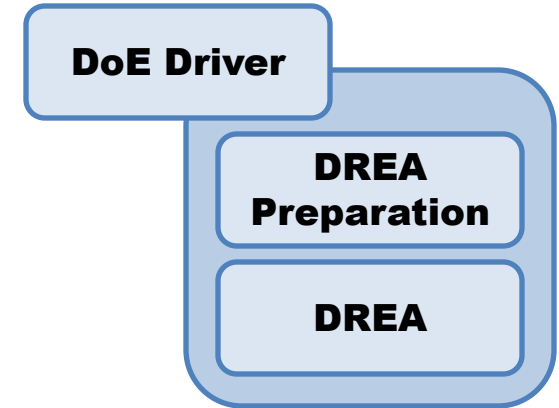
Gross Thrust > 25,000 lbf
CFG > 1.1
OASPL @ 120deg < 142 dB
Primary Pressure: 5075 psf
Length: 8.5 ft
Area Ratio: 2.5
Aspect Ratio: 5
Chute Angle: 9.5 deg



Suppressor Nozzle Off-Design Performance Modeling using DREA/HSRNoise



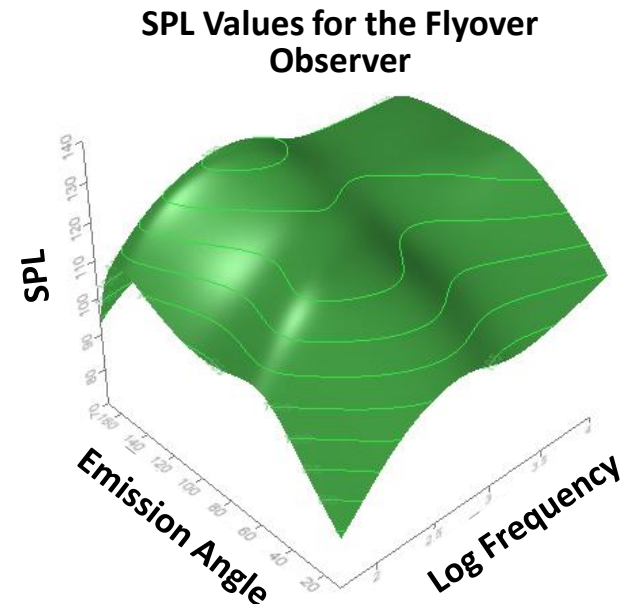
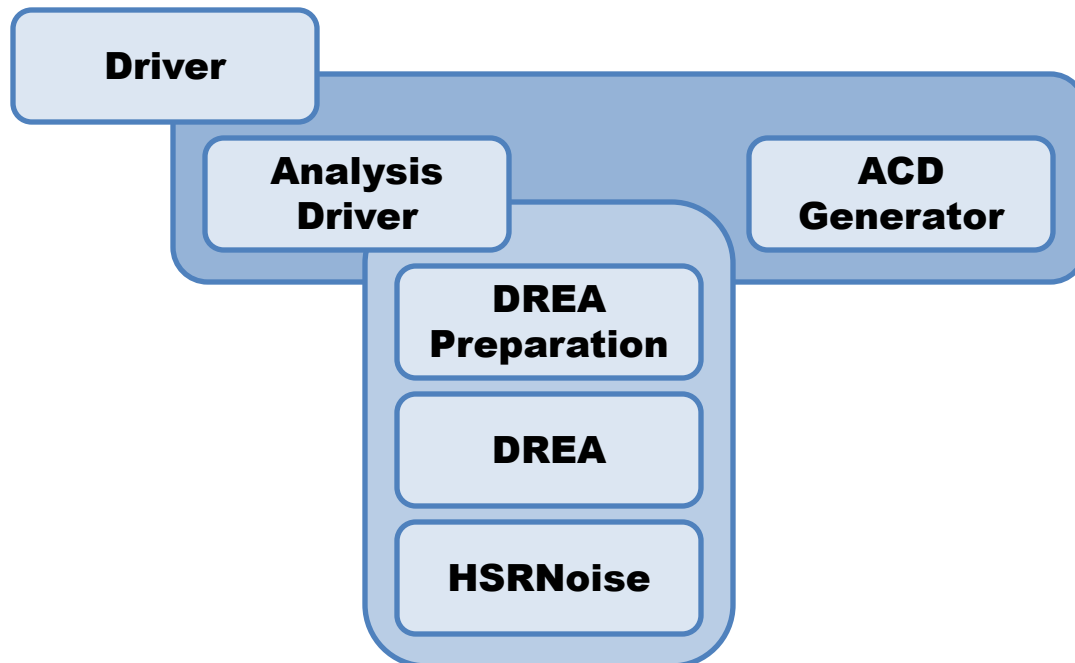
- An OpenMDAO environment was set up to provide off-design performance estimates from DREA for a selected mixer-ejector geometry
- Data for creating the performance maps was generated by executing the OpenMDAO environment on a Design of Experiments (DoE)
- DoE results were imported into the JMP analysis tool and used to create performance maps in the form of response surface equations
 - Map is specific to the geometry selected for analysis
 - Process of creating maps can be repeated for other mixer-ejector geometries
- Performance maps will be integrated into the engine cycle analysis to evaluate the performance trades of mixer-ejectors



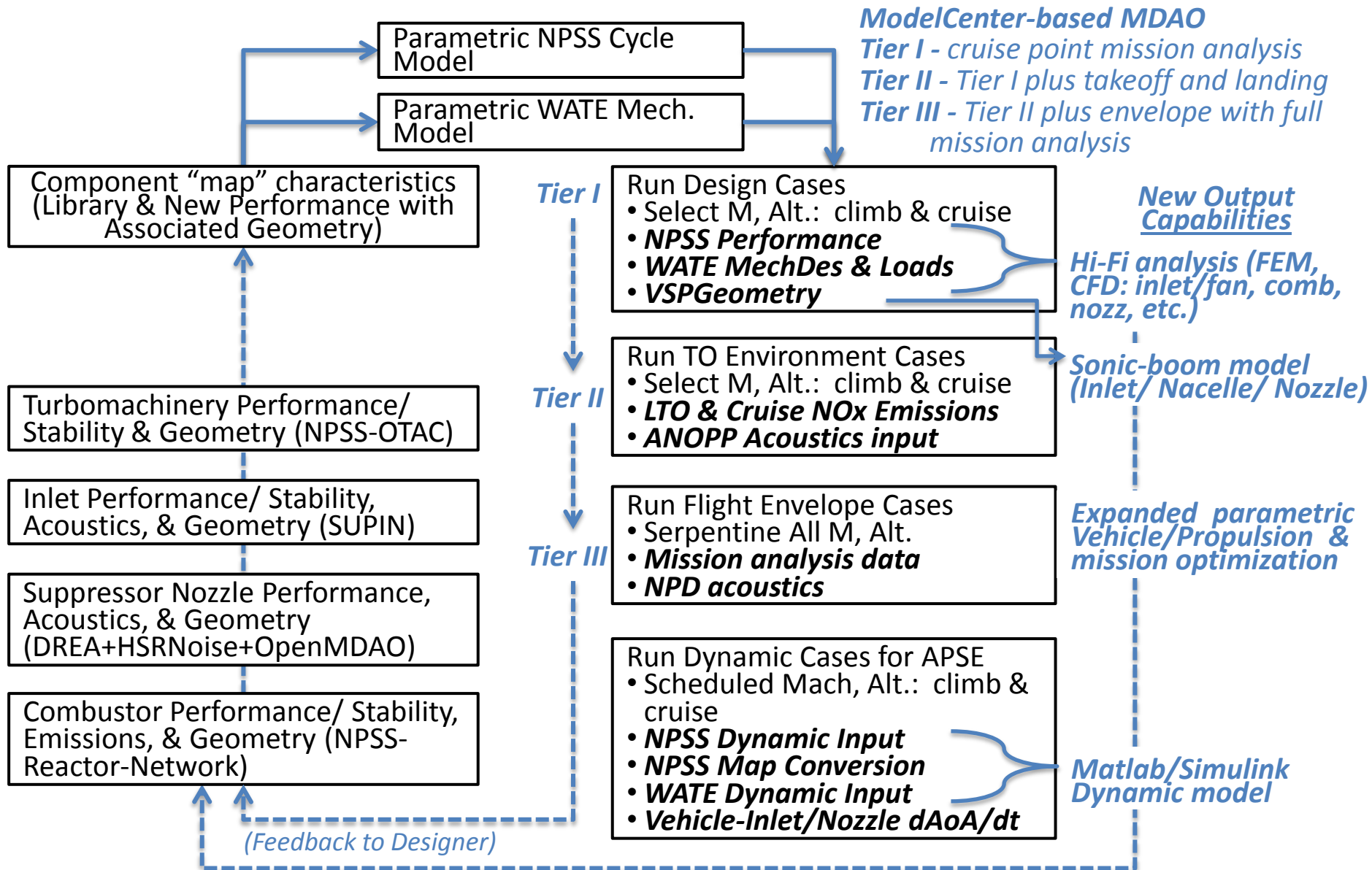
Nozzle Acoustics Modeling using DREA/HSRNoise and ANOPP



- An OpenMDAO environment was created to produce the acoustic data needed for an ANOPP ACD table from the HSRNoise output
- A select set of cases was run to produce the acoustic data required for creating ACD tables at each certification observer point
 - ACD tables are specific to the geometry selected for analysis
 - ACD tables are generated using assumptions about aircraft trajectory and engine power settings
 - Process of creating ACD tables can be repeated for other mixer-ejector geometries and aircraft operating conditions
- ACD tables enable system level acoustic assessment of mixer-ejector nozzles



VCE “Workhorse” for Advancing Multi-disciplinary & Multi-Fidelity Design/Analysis of SUP Propulsion within ModelCenter



Summary Status and Next Steps



- Robust performance and mechanical modeling of MFTF and VCE are completed
 - Next: execute subsystem-optimizations in ModelCenter to narrow design ranges & harness operability parameters (inlet, fan, combustor, nozzle)
 - Next: perform system optimization of emissions and acoustics within ModelCenter (tests interoperability of ModelCenter/OpenMDAO)
- Many engineering elements are completed but most need refinement/implementation, validation, & publishing/dissemination
 - Next: complete structural methods implementation & codify SUP geometries
 - Next: complete & validate Lo-Fi combustor emissions & nozzle performance/acoustics (principally using CFD)
- FY13+ Investigate advanced concepts in the context of the propulsion/mission enabled by new geometry and aerothermodynamic modeling capabilities:
 - 3D Nozzle shielding & velocity contouring with suppressor asymmetry
 - Combustor design and fuel-staging operability trades reconciling LTO vs. supercruise NOx emissions with engine thrust modes
 - Integrated inlet/fan design for installed performance across the flight envelope and T.O. acoustics (NPSS-OTAC, SUPIN, & ANOPP in ModelCenter framework)

